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TECHNICAL NOTE

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A STEADY-STATE, STAGNATION-POINT, HEAT-TRANSFER-RATE MEASURING DEVICE

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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A sensing device is described that is used to measure steady-state convective heat-transfer rate in high-temperature, high-velocity gas streams. The device uses the measurement of axial heat conduction through a cylindrical plug, with one end of the plug at the stagnation point of a hemispherically shaped body exposed to the gas stream.

Experimental tests of three identical probes run through a subsonic Mach number range from 0.2 to 0.8 and a supersonic Mach number range of 2.8 to 3.5 established a correlation factor for the probes with a standard deviation of ±5 percent. The heat input range was 0.7 to 70 (Btu)(ft^{-2})(sec^{-1}).

INTRODUCTION

Studies in reentry heating have been of prime importance in ballistic missile and space vehicle programs. Several theories dealing with stagnation-point heat transfer have been developed to determine the heat input under reentry conditions (refs. 1 to 5). These theories have been corroborated by many investigators who have simulated the conditions and have measured parameters that are important for heat-transfer studies (refs. 6 to 29). These experimental studies were made under both transient and steady-state conditions by using such devices as thin-film gages, thermocouples, calorimeters, and heat-transfer plugs.

Table I summarizes some of the salient features of this previous work. The relation between the experimentally measured and theoretically predicted values in these tests is expressed as a ratio of the values thus obtained.

The stagnation-point heat-transfer-rate probe, herein reported, is a steady-state immersion-type device that exposes a hemispherical-nosed body to the gas stream. A cylindrical, segmented plug thermally insulated from the main body extends from the stagnation point of the blunt body inward to a cooled base in the probe (fig. 1). The plug is made up of three disks sandwiched together. Since the two end disks are of the same material and differ from the central disk, thermocouple junctions are formed at the two interfaces. Under conditions of steady-state, one-dimensional, axial heat flow, the measured temperature drop across the central disk along with the knowledge of its thermal conductivity and

axial length will yield the conductive heat-transfer rate through the plug. For the case of no radial heat exchange, this rate is equivalent to the external heat transferred at the stagnation point of the probe.

In principle, the probe can be used in several ways to yield useful information in high-temperature gas streams. If the probe's measurement is equated to the external convection heat-transfer rate, the total stream enthalpy may be calculated by using the stagnation-point theory. Secondly, the probe can be used to determine the enthalpy profile of a given gas stream. Such information is useful in the calibration of high-temperature test facilities. Also, in test applications where the heat-transfer rate to a given model is of primary interest, the probe may be used to determine the heat-transfer rate to itself; then, using geometric considerations, the heat-transfer rate to the model may be predicted. Other steady-state heat-transfer-rate devices are described in references 7, 8, 10, 14, 15, 23, 24, and 26. The devices of references 8, 14, and 23 use the segmented type of construction for the heat-transfer plug.

This report presents the correlation results from three probes of the design shown in figure 1. These devices were tested in three different tunnel facilities over a subsonic Mach number range of 0.2 to 0.8 and a supersonic Mach number range of 2.8 to 3.5 with heat flux ranging from 0.7 to 70 (Btu)(ft^{-2})(sec^{-1}).

This work is part of a program in high-temperature measurements being conducted at the NASA Lewis Research Center.

SYMBOLS

a	free-stream velocity of sound
C	velocity gradient at stagnation point
H	enthalpy
k	thermal conductivity
l	axial length
M	Mach number
P	total pressure
Pr	Prandtl number
p	free-stream static pressure
Q_m	measured heat-transfer rate per unit area
Q_{th}	theoretical heat-transfer rate per unit area
R	hemisphere radius

ΔT temperature drop across center heat-transfer disk

γ ratio of specific heats

ρ density

μ viscosity

Subscripts:

o stagnation conditions

w wall

1 conditions in front of body (but behind shock wave for supersonic flow)

HEAT-TRANSFER CALCULATIONS

Heat Conduction Through Plug

The equation for steady-state, one-dimensional, conductive heat flow through a solid is, for a unit area,

$$Q_m = \frac{k(\Delta T)}{l} \tag{1}$$

If it is assumed that this equation applies to the sensing plug, Q_m is the heat-transfer rate per unit area, ΔT is the temperature drop across the center disk, k is the thermal conductivity of the center disk material, and l is the axial length of the center disk.

Theoretical Convective Heat Transfer to Stagnation Point

The external convective heat-transfer rate to the stagnation point, when using reference 5 for the case when gas dissociation is negligible, can be expressed as

$$Q_{th} = 0.75\ Pr^{-0.6}(\rho_w\mu_w)^{0.1}(\rho_o\mu_o)^{0.4}(H_o - H_w)\sqrt{C} \tag{2}$$

APPARATUS

Heat-Flux Probe

Design considerations. - Some test results using a plug-type heat-flux probe have been reported in reference 24. This device was fairly simple in design. It used a single-material heat-transfer plug with thermocouple wires for measuring axial temperature drop attached at the side surface and had metal-to-metal side contact areas at both end portions of the plug (fig. 2). A test program using

this design resulted in inconsistencies in correlating the measurements with the theoretically calculated heat input; the measured stagnation-point heat flux was generally greater than that predicted. Reference 29 reports that, in an arc-tunnel application, a flat-nosed and a blunt-nosed probe using the general design of figure 2 also indicated heat-transfer rates greater than those obtained by a tunnel heat balance measurement. The author of reference 29 subsequently attributed this disagreement to radial heat input at the forward metal-to-metal contact area, since a "loosening" of the fit between the stagnation plug and its hemispherical envelope gave results that were in good agreement with other measurements.

The experience with the simple design of figure 2 seemed to indicate that radial heat flow in the plug and the inability to control the front metal-to-metal fit were the primary reasons for inconsistencies and deviations from the ideal axial heat flow through the plug.

Design changes resulted in the probe herein reported. The heat-transfer plug was mounted in its hemispherical envelope using a high-temperature cement at the nose annulus and an epoxy resin at the cooled base annulus. A segmented plug was also used to give interface temperatures that might be more representative of the heat flow through the plug than the side surface thermocouple junctions.

Figure 1 shows the sensing-head design details of the probe used in the present report. Three probes were constructed and tested to check reproducibility. The triple-disk plug thermocouple design with the three attached thermocouple wires makes it possible to measure the axial temperature drop across the center disk as a direct differential reading and also to measure the absolute temperature at either or both interfaces. The differential measurement is the ΔT value used in equation (1), and an interface temperature is necessary to measure the temperature level of the center disk to relate to its thermal conductivity k.

The 1/4-inch-radius hemispherical sensing head was mounted on a 1/4-inch-radius, cylindrical support tube, and a single water supply was used for both the support tube and plug-base coolant.

Plug material considerations. - In order to calibrate a heat-transfer probe in a flow environment, it is necessary to calculate the heat input from knowledge and measurement of stream parameters involved in equation (2). No single steady-state facility was available that was suitable to evaluate this heat-transfer device over a large Mach number range with high heat fluxes. Testing was therefore confined to three facilities operating at ambient and moderately high temperatures, but whose flow environments were suitable for defining the stream parameters necessary for testing the probe. Because of the lower heat input rates of these tunnels, the choice of material used in the central disk was such as to obtain a sufficient temperature drop (by virtue of its thermal resistance) and an adequate thermocouple signal when paired with copper, which was the choice of material for the hemispherical-nose and end disks. The experimental design herein reported uses constantan for the central disk, since it forms a well-established thermocouple pair with copper and has a low thermal conductivity. For higher heat inputs, platinum could be considered for use as the central disk

to form a copper-platinum thermocouple system.

Velocity Gradient Model

The theoretical equation (2) is predicated on a certain velocity distribution at the nose. To confirm that such a distribution actually existed, there was included in the investigation a 1/4-inch-radius hemispherical-nosed probe with static-pressure taps along the nose (fig. 3). These taps (0.010-in.-diam. holes) were located at 5° intervals up to 30° from the stagnation point. This model was run in the subsonic free-air jet and the Mach 1.4 tunnel described in the next section.

Tunnel Test Facilities

Subsonic free-air jet. - This facility operated from a continuous pressurized supply of room-temperature air, which flowed from a plenum chamber through a $3\frac{1}{2}$-inch-diameter nozzle and exhausted into a room at atmospheric pressure. The Mach number range was from 0.2 to 0.8. A further description of this facility can be found in reference 30.

Combustion tunnel. - This tunnel uses the exhaust gas from the combustion of gasoline and air. This exhaust gas passes from the combustor plenum through a converging nozzle with a 3-inch-diameter throat and into a 12-inch-diameter receiving duct. Separate controls for the flow of fuel and air and for inlet and exhaust pressures provide independent control of temperature, Mach number, and pressure at the test section. Tests were performed in this tunnel with and without combustion, at a total pressure of 1 atmosphere, over a Mach number range from 0.2 to 0.8. Preheaters were used for the noncombustion runs and supplied air to the test section at a total temperature of 630° R. The tests with combustion were made at a total-temperature level of 1960° R. This tunnel is described in detail in reference 31.

10- by 10-foot supersonic tunnel. - Further tests were made in the Lewis 10- by 10-foot supersonic tunnel where the probes were mounted on a single strut (fig. 4) and run as a secondary test along with a major tunnel program involving a test vehicle. These runs covered a Mach number range from 2.8 to 3.5 and a temperature range from 650° to 750° R, with total pressure from 1.2 to 2.2 atmospheres.

Mach number 1.4 tunnel. - This tunnel operates from a continuous supply of pressurized, room-temperature air that flows through a convergent-divergent nozzle having a 3- by 4-inch throat and exits into a 12-inch-diameter circular exhaust duct. This tunnel is described in reference 30.

TEST AND RESULTS

Velocity Gradient Model

The experimental data obtained with the velocity gradient model showed good

agreement with a velocity gradient parameter derived from reference 2. These results are presented in figure 5.

Ratio of Theoretical to Measured Heat Input

The ratio of theoretical to measured heat input as a function of heat input and Mach number is shown in figure 6. The tunnels listed in figure 6(a) are identified in the section entitled Tunnel Test Facilities. The experimental accuracy was estimated to be on the order of 5 percent. The greatest uncertainty at the low heat inputs was attributed to the measuring accuracy of the small thermocouple signal, and the greatest uncertainty for the high-temperature runs was in the knowledge of the transport properties for the hot gas.

DISCUSSION OF RESULTS AND CONCLUDING REMARKS

The probe consistently indicated a lower heat input than predicted by theory. The value of the ratio Q_{th}/Q_m was 1.3 with a standard deviation of ±5 percent. This correlation factor (1.3) indicates a 30-percent heat loss in the measuring system. The bulk of this loss could be due to a radial flow of heat out of the heat-transfer plug across the forward cemented annulus into the hemispherical envelope. The radial temperature gradient across this forward cemented annulus would be provided by the thermal resistance of the constantan disk, which raises the front copper disk temperature above the temperature of its surrounding hemispherical shell by an amount approximately equivalent to the axial temperature drop (ΔT) through the constantan disk. A calculation based on this premise yields the same order of magnitude loss as that experimentally obtained.

This loss could be decreased by reducing the annulus contact area and optimizing the central disk length and material for a given application so that the temperature differential across the cemented annulus is reduced. For instance, if the central disk of constantan in the present design were replaced with platinum, the temperature "driving force" across the cement annulus would be reduced approximately by a factor of 3. This choice of material was not used in the present tests, since the combination of reduced temperature drop and reduced thermoelectric signal from a copper-platinum pair would have had an overall reduction in the signal by a factor of 18 and would have provided an inadequate signal for measuring the lower heat inputs in the present program.

As previously mentioned, a central platinum plug could be considered for a high-heat-flux design, as might be used in an electric-arc jet temperature measurement. However, it is recommended that changes in material or design should be accompanied by a new calibration-factor determination.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 22, 1963

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TABLE I. - SUMMARY OF STAGNATION-POINT HEAT-TRANSFER DATA

Reference number	Facility	Model	Flow duration	Mach number	Total temperature, ^{o}R	Test condition	$\frac{Q_{th}}{Q_m}$
6, 9, 13	$1\frac{1}{2}$"-4" Shock tube	1/2"-1" Hemispheres; heat-sink and thin-film gages	10-100 μsec	≈3	≈10,000	Altitude, 20,000-120,000 ft	1.28-0.75
7	5" × $6\frac{1}{2}$" Wind tunnel	$1\frac{3}{4}$" Hemisphere; ΔT across model wall with thermocouples	Steady state	7.8	760-1260	Total pressure, 115-365 lb/sq in. abs	1.16-0.85 After meters were calibrated
8	1' × 1' Blowdown tunnel	2" Hemisphere; ΔT across thickness of constantan	Steady state	2-4	560-1150	Reynolds number/ft, 7×10^6-44×10^6	1.14-0.80 After correction factor was applied
11	$3\frac{3}{4}$" Shock tube	1" Hemisphere; thin-film gages	0.1-0.5 msec	1.7-2.6	3000-8000	Reynolds number, 0.3×10^5 3.6×10^5	1.82-0.69
12	16"-Diam. Hot-shot tunnel	4" Hemisphere; heat-sink gages	25 msec	11-19	7000-14,000	Reynolds number/ft, 5×10^4-2.5×10^5	1.45-0.80 After meters were calibrated
14	12" × 13" Blowdown tunnel	1.1"-Diam. cylinder; ΔT across thickness of constantan	Steady state	4.1	600-760	Reynolds number, 1×10^6-4×10^6	1.0-0.91 After meters were calibrated and flange correction applied
15	1/2"-Diam. arc jet	Water-cooled flat-plate calorimeter	Steady state	Subsonic	7400-12,000	Room pressure	1.15-0.87
25	11" Hypersonic tunnel	1"-3" Thin-walled hemisphere with thermocouples in walls	-----------	6.8	1000	Reynolds number, 2×10^4-15×10^4	1.06-1.02
26	6' × 9' Ice tunnel	20"-Diam. spinner; thermocouples in walls	Steady state	0.1-0.2	460	Reynolds number, 1×10^4-1×10^5	1.15-1.00
27	1' × 1' Wind tunnel	R = 0.7"; thin-wall hemisphere-cone-cylinder; thermocouples in wall	Model cooled and then heated up to tunnel temperature; no time given	3.1	520	Reynolds number, 3×10^5 12×10^5	1.04-0.98 Down to 0.67 for 130-microin. roughness
28	12" and 27" Blowdown jets	4" And 12" flat-face thin-skin models; thermocouples in skin	2 sec	2	960	Sea-level static pressure	1.05-0.80
29	2.7"-Diam. arc jet	1/2" Hemisphere	Steady state	4-5	3000-9000	Total pressure, 2mm Hg	1.10-0.90

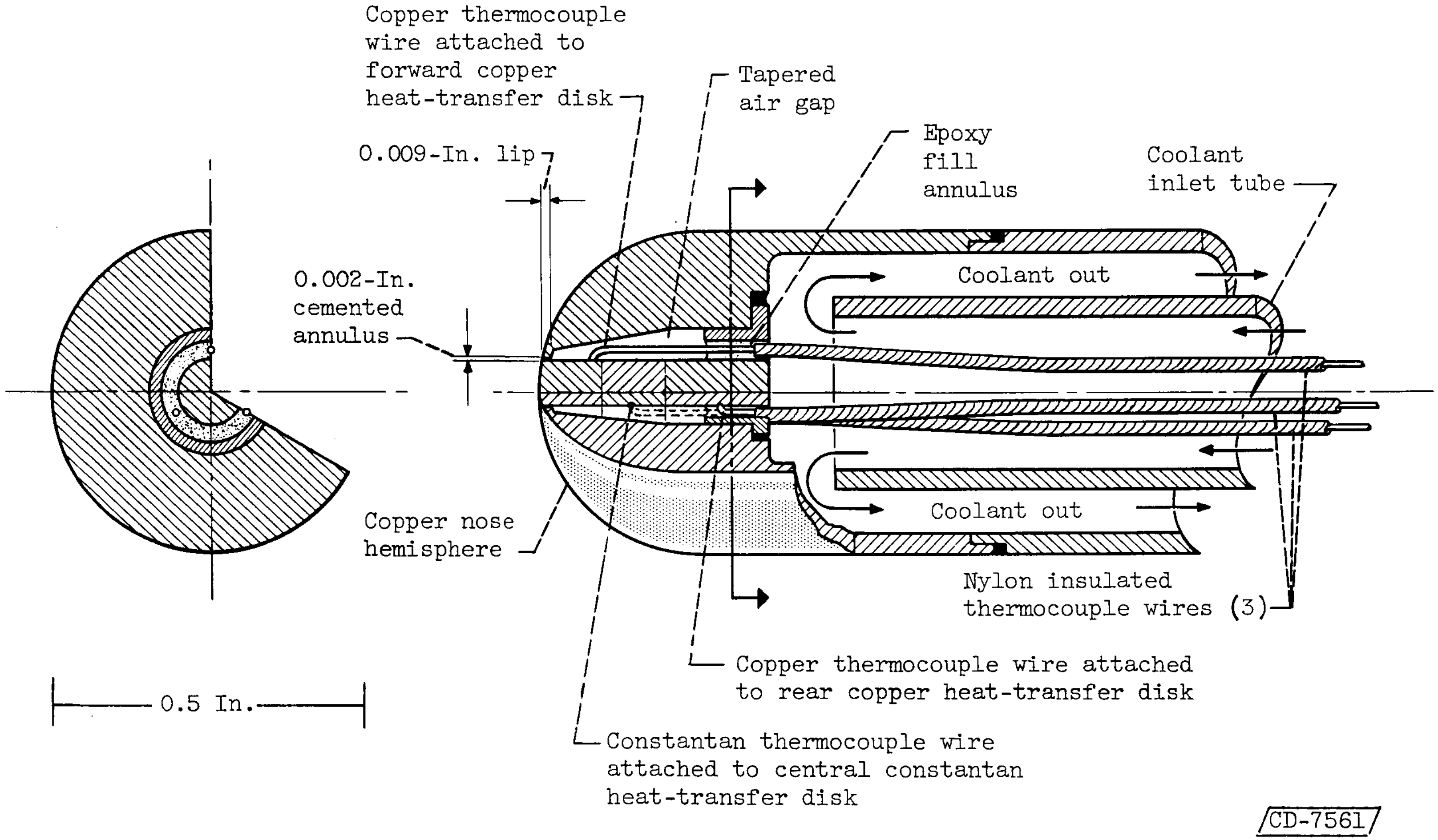


Figure 1. - Segmented-plug-type heat-transfer probe.

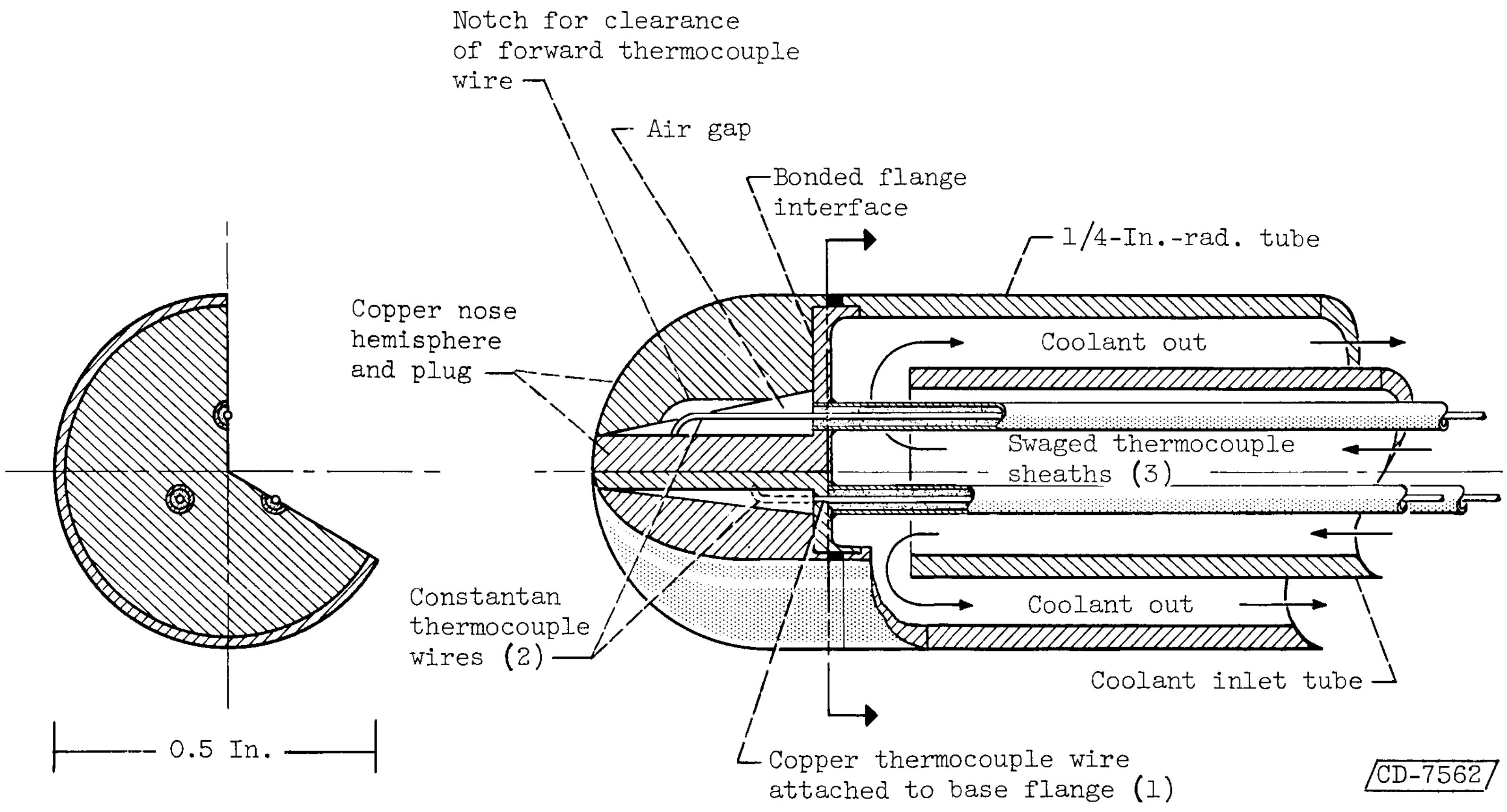


Figure 2. - Plain-plug-type heat-transfer probe.

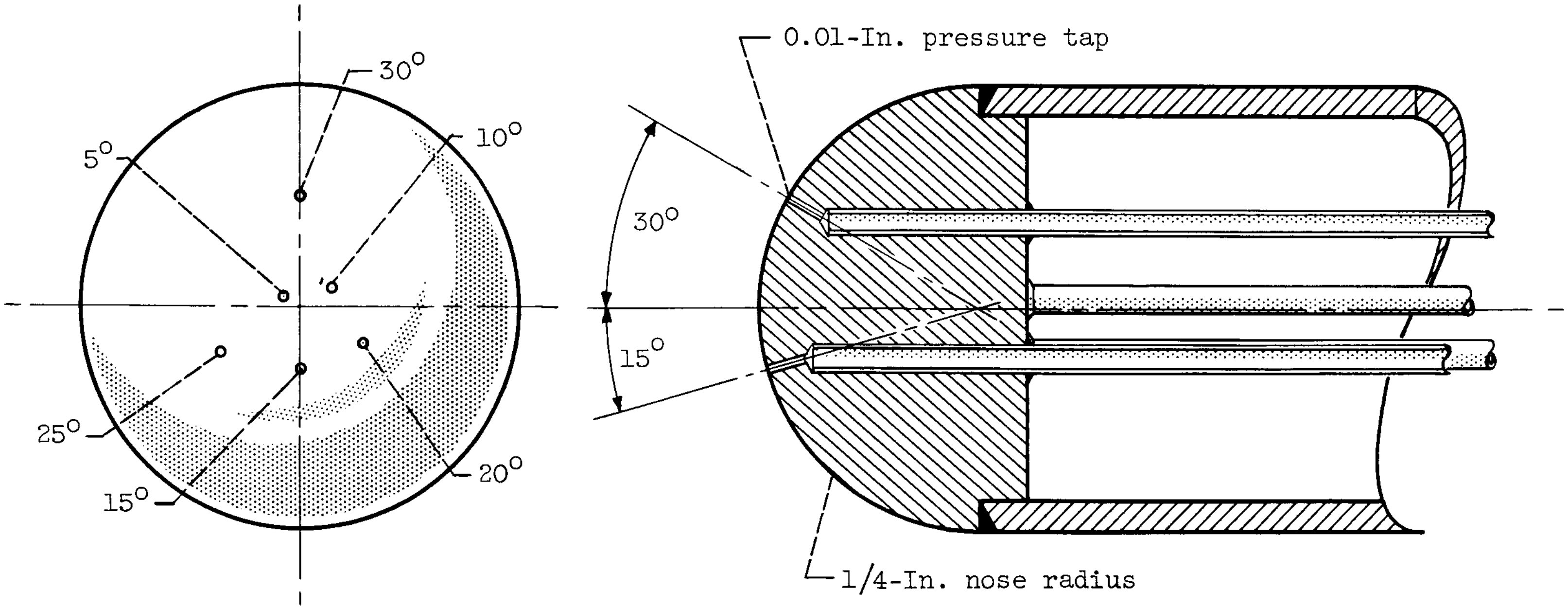


Figure 3. - Pressure distribution model.

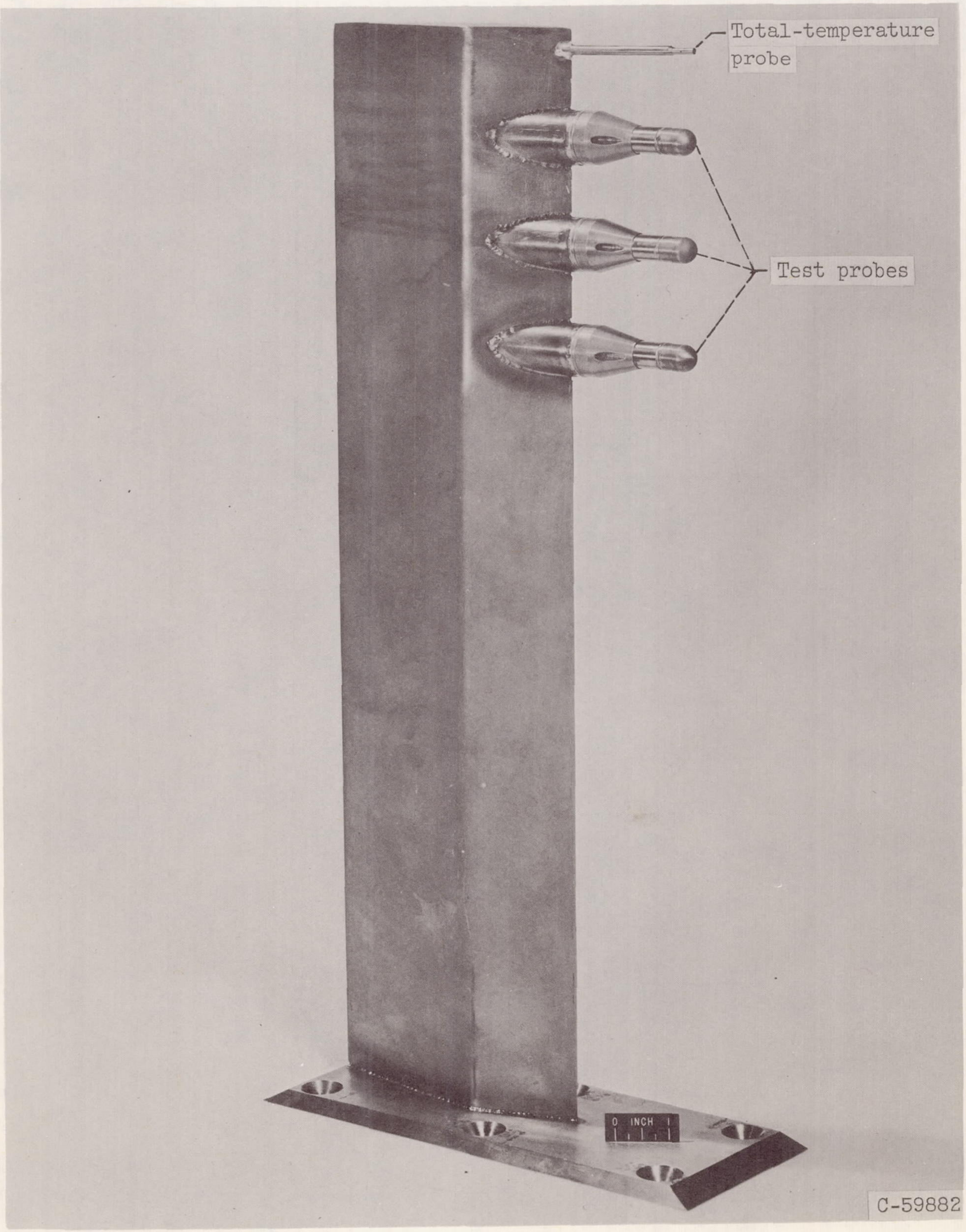


Figure 4. - Strut mounting for supersonic tests.

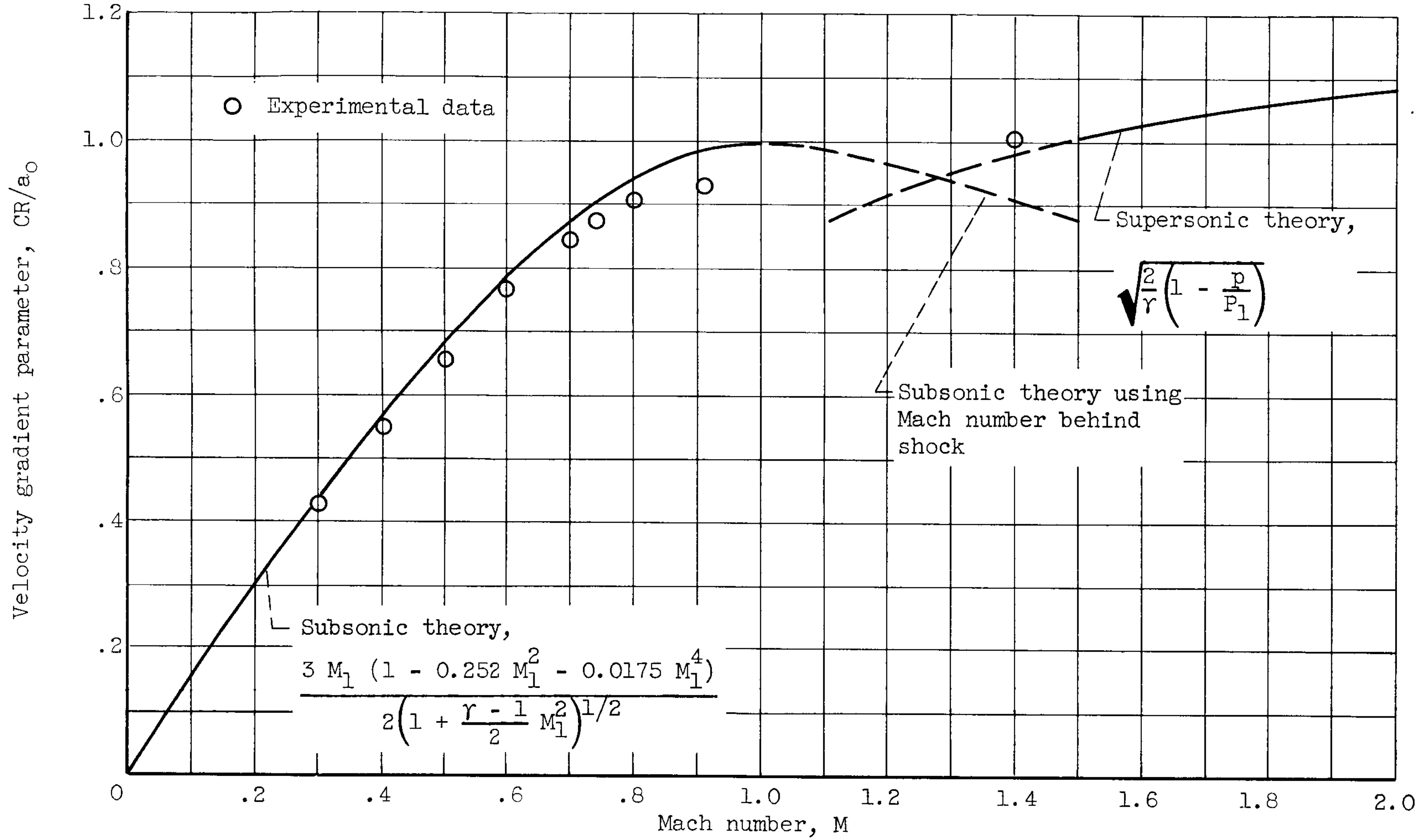
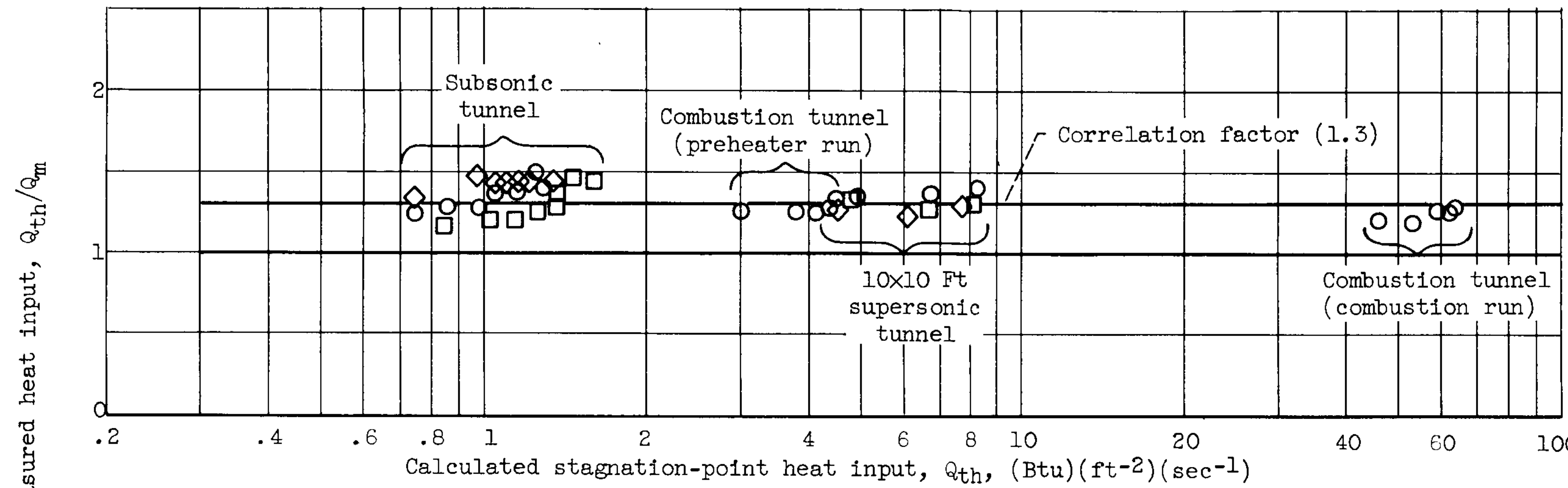
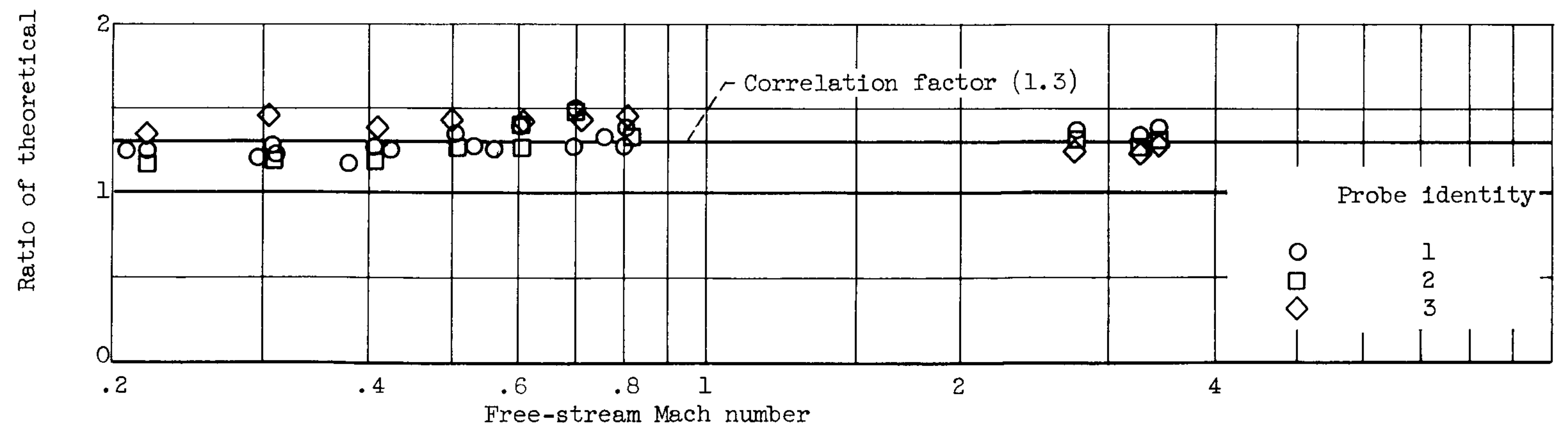


Figure 5. - Effect of Mach number on velocity gradient parameter for a 1/4-inch-radius hemisphere model.



(a) As a function of heat input.



(b) As a function of Mach number.

Figure 6. - Ratio of theoretical to measured heat inputs.

NASA-Langley, 1963 E-1009